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Indirect Searches for Dark Matter with the *Fermi* Large Area Telescope☆

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Abstract

There is overwhelming evidence that non-baryonic dark matter constitutes ~27% of the energy density of the Universe. Weakly Interacting Massive Particles (WIMPs) are promising dark matter candidates that may produce γ rays via annihilation or decay detectable by the *Fermi* Large Area Telescope (LAT). A detection of WIMPs would also indicate the existence of physics beyond the Standard Model. We present recent results from the two cleanest indirect WIMP searches by the *Fermi*-LAT Collaboration: searches for γ-ray spectral lines and γ-ray emission associated with Milky Way dwarf spheroidal satellite galaxies.

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1. INTRODUCTION

Astrophysical observations imply that ~ 27% of the energy density of the Universe is non-baryonic cold dark matter (DM) [1]. While substantial astrophysical evidence exists for DM through its gravitational interaction, little is known about the composition of the DM or its properties and many theoretical candidates have been proposed. A popular class of models [2, 3, 4] predict the DM is a weakly interacting massive particle (WIMP), which we denote by χ. If we assume WIMPs explain all of the DM in the Universe and are a thermal relic (i.e. were in thermal equilibrium in the early Universe), then we expect them to have a mass in the GeV to TeV range and an *s*-wave annihilation cross section of $\sim 3 \times 10^{-26}\,\mathrm{cm^3\,s^{-1}}$ (see Ref. [5] for a recent, precise calculation of $\langle\sigma v\rangle$). If such WIMPs exist and annihilate into standard model particles with that cross section, then we should be able to detect signatures of such interactions in regions of high DM density. One such signature would be the creation of γ rays with a continuum of energies via annihilations into intermediate states (e.g. $\chi\chi \rightarrow b\bar{b}$). As the original annihilation (and subsequent daughter) particles propagate, γ rays will be produced. This smooth continuum signature is difficult to distinguish from the γ-ray spectra other astrophysical processes. Therefore, it is challenging to search for potential DM γ-ray signals in astrophysically complex regions of the sky like the Galactic center. Dwarf spheroidal satellite galaxies of the Milky Way are regions with a large amount of DM and negligible (non-DM) astrophysical γ-ray processes. Those that are located far enough away from the Galactic plane also have low diffuse Galactic foregrounds. Therefore dwarf galaxies are relatively clean targets for searches for γ rays from DM. Another "clean" (i.e. containing negligible

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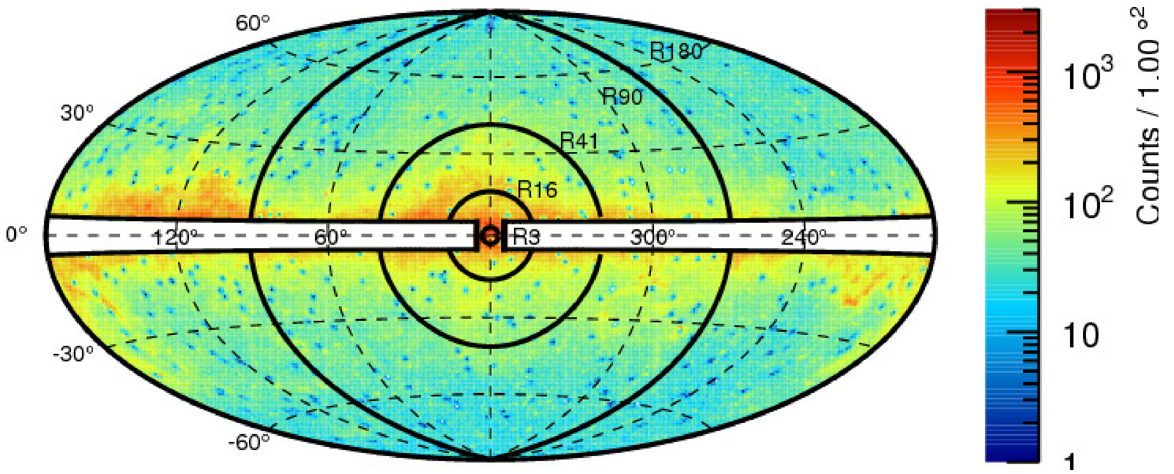

Figure 1. Counts map for the line search dataset binned in $1^\circ \times 1^\circ$ spatial bins in the R180 ROI, and plotted in Galactic coordinates using the Hammer-Aitoff projection. Also shown are the outlines of the other ROIs (R3, R16, R41, and R90) used in this search. Same as Fig. 2 in Ref. [7]

background) search for a γ-ray DM signature is to search for γ-ray spectral lines. DM annihilation directly into γ rays ($\chi\chi \to \gamma\gamma$) will produce monochromatic γ rays with $E_\gamma = m_\chi$. Note that DM annihilation (or decay) into a γ ray and a neutral particle (e.g. Z^0 boson) will also produce a monochromatic signal at a shifted energy. No other astrophysical processes are expected to produce such a narrow γ-ray spectral feature. Here we present results from searches for these two DM searches by the *Fermi*-LAT Collaboration. Both our search for γ rays from the dwarf galaxies and our search for spectral lines have resulted in two publications in PRD [6, 7] and we refer the reader to those works for details regarding the results summarized here.

2. LAT INSTRUMENT AND DATA SELECTION

Both searches use data collected by the Large Area Telescope (LAT) on board the *Fermi* γ-ray space telescope. The LAT is a pair-conversion telescope that observes the entire γ-ray sky from 20 MeV to >300 GeV every 3 hours (while operating in normal survey mode). Details regarding the LAT and its performance can be found in Refs [8, 9]. Additionally, a brief summary of the LAT instrument and event selections can be found in Sec.II of Ref [7]. Both searches obtained their datasets using the `P7REP_CLEAN` event selection. Additionally, events with a zenith angle $>100^\circ$ were removed from both datasets to remove excess emission from the bright limb of the Earth.

The dwarf galaxy dataset contained events taken in the first four years of operation (2008-08-04 to 2012-08-04) in the energy range 500 MeV to 500 GeV. 25 dwarf galaxies were considered in $14^\circ \times 14^\circ$ regions-of-interest (ROIs) centered on each dwarf galaxy. The data were binned in 0.1° pixels and 24 logarithmically-space energy bins.

The line search dataset contained events taken in the first 3.7 years of operation (2008-08-04 to 2012-04-12) in the energy range 2.6 to 541 GeV. Bright γ-ray point sources from the 2 year *Fermi* point-source catalog [10] were masked. 4 different ROIs were obtained from optimizing the $(S)/\sqrt{B}$ for DM annihilation assuming 4 different Galactic DM density profiles: contracted NFW ($\gamma = 1.3$), Einasto [11], NFW [12], and isothermal [13] (see Sec.III of Ref. [7] for details). Additionally, a large full-sky (minus the background-dominated off-center Galactic plane) ROI was used to search for a monochromatic signal from DM decay. We call the ROIs R3, R16, R41, R90, and R180 respectively. Figure 1 shows all 5 ROIs used in the line search.

3. DWARF GALAXY SEARCH RESULTS

A maximum likelihood analysis was performed for each dwarf galaxy to search for excess γ-ray emission consistent with the expectation from 6 DM annihilation channels ($e^+e^-, \mu^+\mu^-, \tau^+\tau^-, u\bar{u}, b\bar{b}$, and W^+W^-) for masses from

2 GeV to 10 TeV. The non-DM components of the fits were a diffuse Galactic background model, an isotropic background (from residual cosmic rays and extragalactic γ-ray emission) model, and γ-ray sources from the 2-year *Fermi* point-source catalog [10]. No significant emission was detected from any of the 25 dwarf galaxies for any annihilation channel or mass considered. To derive limits on the DM annihilation cross section, a joint-likelihood analysis was performed. Only 15 of the 25 dwarf galaxies were used. 7 galaxies were excluded because they did not have kinematically-determined DM content measurements (”J factors”[1]). 3 additional dwarfs were excluded due to overlapping ROIs. By combining the likelihoods of all 15 dwarfs, stronger limits are obtained than from each individual dwarf galaxy. Figure 2 shows the 95% confidence level (CL) dark matter cross section annihilation upper limits obtained in this search. The expected sensitivity (dashed line) is shown with the expected 68% and 95% containment given both statistical fluctuations and the systematic uncertainty in the diffuse Galactic foreground modeling. We estimate the uncertainty in the diffuse modeling by fitting in 300 random blank field ROIs. The observed limits all lie with the 95% containment of the expected sensitivity. No significant detection of a γ-ray excess was observed in the dwarf galaxy search.

Sensitivity is expected to significantly improve for future dwarf galaxy searches with LAT data. Figure 3 shows the expected sensitivity of a future dwarf analysis given 10 years of LAT data and 35 dwarf galaxy targets. Besides the 9 classical dwarf galaxies, the other known dwarf galaxies were detected using the Sloan Digital Sky Survey, which was only performed in the northern hemisphere. Next generation surveys (many of which will survey the southern hemisphere), like the Dark Energy Survey, are expected to discover more dwarf candidates. As the LAT surveys the entire sky, additional dwarf galaxies will be able to make use of the full LAT exposure.

4. LINE SEARCH RESULTS

We performed a maximum likelihood analysis to search for spectral lines from 5 to 300 GeV in 5 ROIs. We fit in sliding energy windows of $\pm 6\sigma_E(E_\gamma)$, where $\sigma_E(E_\gamma)$ is the energy resolution (68%) at the fit energy. Since we fit in narrow energy windows, we approximate the background spectrum to be a power law and allow the index to float in the fit. We use an energy dispersion model that incorporates the quality of the energy reconstruction on an event-by-event basis (see Sec.IV of Ref. [7] for more details). We find no significant detections an therefore set limits on the dark matter cross section for annihilation to γ rays$\tilde{(}$see Fig. 4). Note that the green and yellow bands show the 68% and 95% containment of the expected sensitivity based on statistical fluctuations only. We also compare our limits to those obtained by an independent analysis [14] and note that similar results were obtained in both analyses.

Our most significant fit occurred in our smallest ROI (R3, a 3° Galactic center ROI) at 135 GeV. This is the same feature reported in earlier works at 130 GeV [15, 14], but the energy has shifted due to the use of a dataset reprocessed with updated calorimeter calibration constants. The significance of the 135 GeV feature is less than other works (1.5σ global) and the feature in the data is significantly narrower than the expected LAT energy dispersion. When allowing a scale factor (between 0 and 1) on the width of the energy dispersion model to float in the fit, a value $s_\sigma = 0.32^{+0.22}_{-0.07}$ was preferred where the quote errors are at the 95% confidence level. This points to a non-physical explanation of the feature like a statistical fluctuation. Additionally, we did a cross check using data from the bright Earth's Limb. These are γ rays produced by cosmic ray interactions in the upper atmosphere of the Earth. Above 3 GeV, we expected the energy spectrum to follow a simple power law and contain no line-like features. Therefore this is a very useful control region for our line search. We detect a small line-like feature in the Earth Limb at 135 GeV, which seems to be caused by energy-dependent variations in the LAT effective area. While this feature in the Limb cannot account for all of what is seen in the Galactic center, it does suggest that a systematically induced line-like feature may be partially responsible for the Galactic center feature. We also show that with increased exposure (4.4 years vs. 3.7 years), the 135 GeV feature in the Galactic center is shrinking rather than growing. The local significance of the 135 GeV feature in R3 was 3.2σ in the 3.7 year dataset and 2.9σ in the 4.4 year dataset. This supports the hypothesis that the feature is predominantly a statistical fluctuation.

[1]The J-factor encapsulates the amount and spatial distribution of dark matter in each dwarf (see Eq.6 in Ref. [6]). The uncertainty in the J-factors of each dwarf galaxy were incorporated in the final limits.

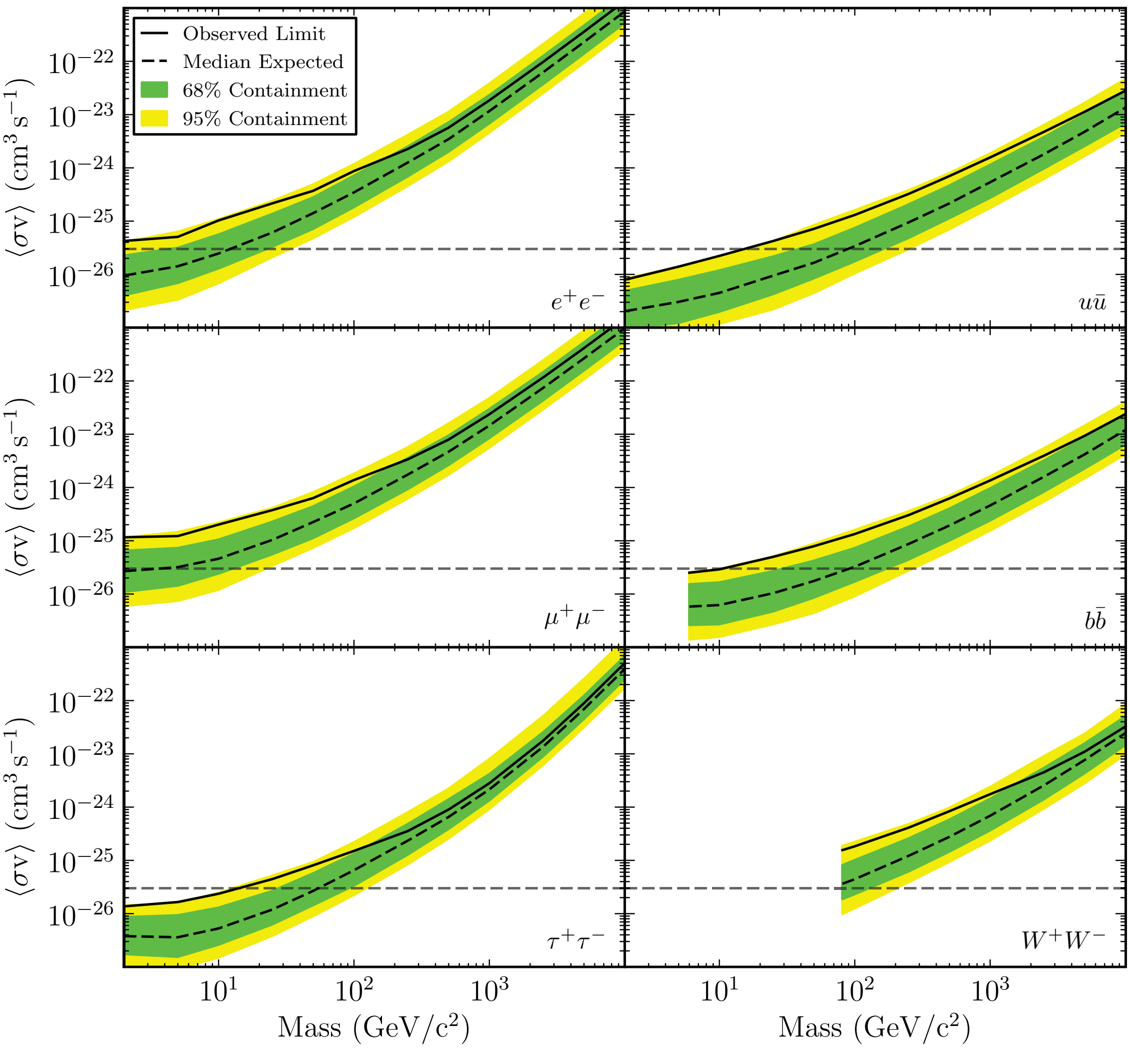

Figure 2. 95% CL dark matter annihilation cross section upper limits from a combined analysis of 15 dwarf galaxies using 4 years of data. The dashed line shows the expected sensitivity for this search. The green and yellow bands show the 68% and 95% containment of the expected limit sensitivity given both statistical fluctuations and systematic uncertainty in the Galactic foreground modeling. The latter was approximated by fits to 300 random blank field ROIs at high latitudes. Same as Fig. 5 from Ref. [6]

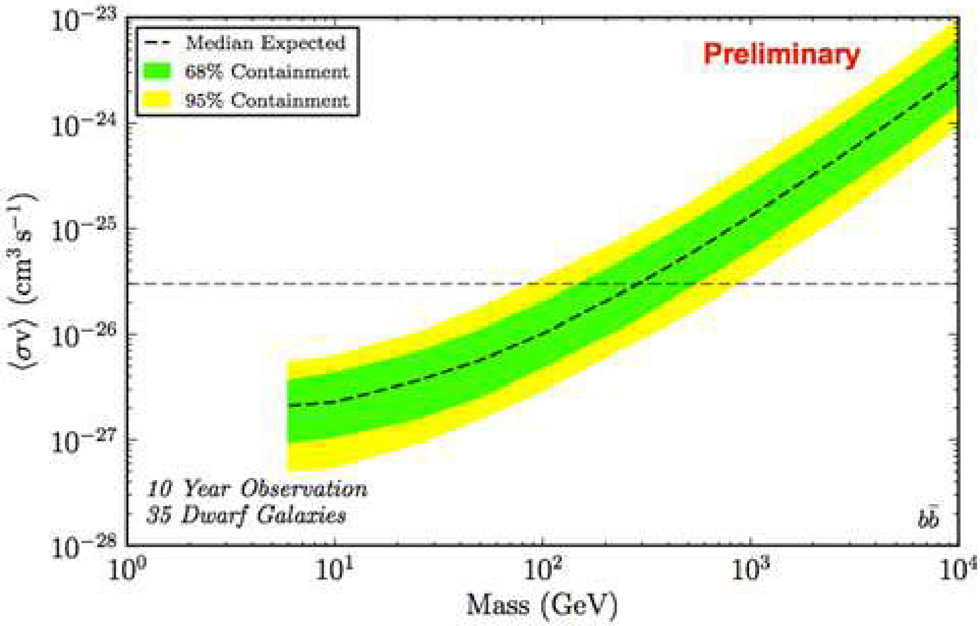

Figure 3. Expected sensitivity from a future dwarf galaxy analysis with 10 years of data and 35 dwarf galaxies.

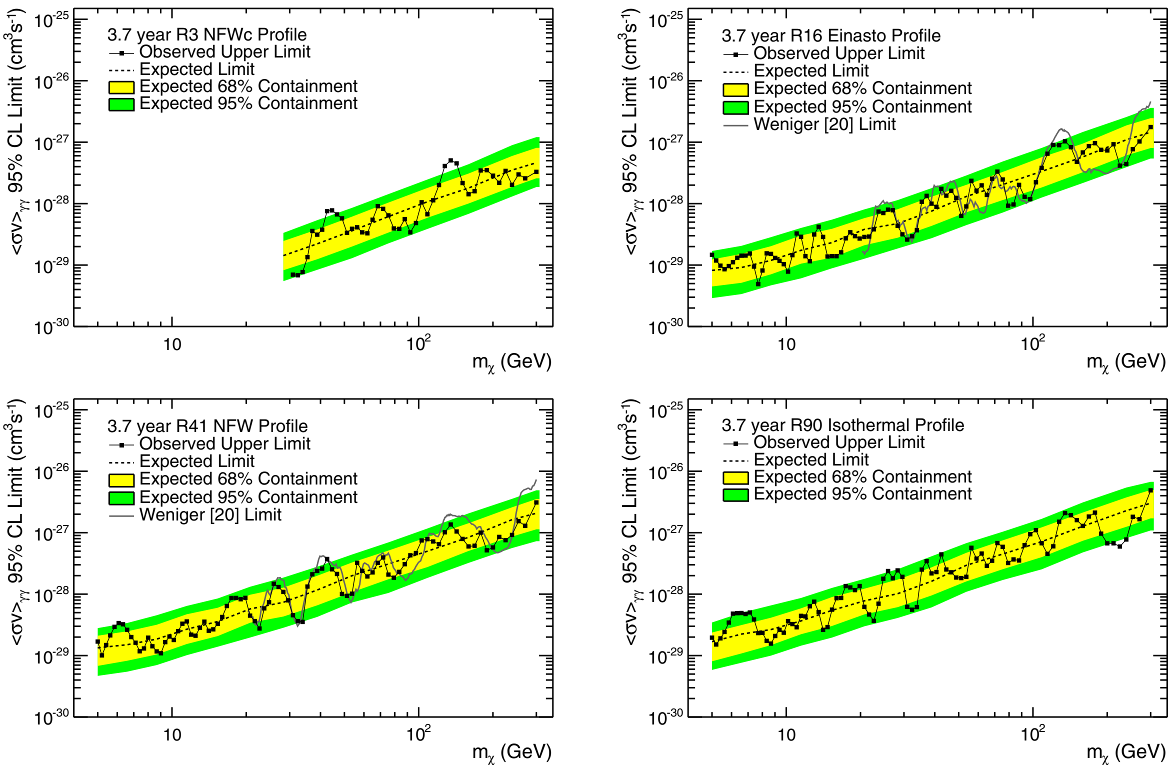

Figure 4. 95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ upper limits for each DM profile considered in the corresponding optimized ROI. Yellow (green) bands show the 68% (95%) expected containment derived from 1000 single-power law (no DM) MC simulations. The dashed lines show the median expected limits from those simulations. The solid gray line shows the limits derived by [14] (an independent search for spectral lines from 20−300 GeV) when comparable ROIs and identical DM density profiles were used. Same as Fig. 10 from Ref. [7]

5. SUMMARY

The *Fermi*-LAT Collaboration has searched for excess γ rays from DM annihilation a variety of ways. Our two "cleanest" searches have been searching for γ-ray emission from dwarf galaxies and also searching for γ-ray spectral lines. We presented the results from the two most recent iterations of these searches using 4 and 3.7 years of data respectively. Neither search had a significant detection of a DM signal and we have set strong limits on the dark matter annihilation cross section.

All LAT analyses, including these specific searches, are expected to improve with increased LAT exposure and understanding of the LAT instrument.

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